

Neutrino-induced coherent pion production

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Abstract. We have investigated the neutrino induced coherent pion production reaction at the energies of interest for recent experiments like K2K and MiniBooNE. The model includes pion, nucleon and the $\Delta(1232)$ resonance. Medium effects in the production mechanism and the distortion of the pion wave function are taken into account. We find a strong reduction of the cross section due to these effects and also substantial modifications in the energy distributions of the final pion. The sensitivity of the results on the axial N- Δ coupling $C_5^A(0)$ and the coherent fraction in neutral-current π^0 production are discussed.

Keywords: Neutrino-nucleus interactions, N- Δ form factors, Pions in the nuclear medium

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The coherent production of pions in charged current (CC) and neutral current (NC) processes is a subject of research in current and future experiments. The K2K collaboration has not found any evidence of $\nu_\mu + {}^{12}\text{C} \rightarrow \mu^- + \pi^+ + {}^{12}\text{C}$, obtaining an upper limit for the coherent fraction over the total CC interaction [1] well below the estimates based on the Rein and Sehgal model [2]. On the other side, preliminary MiniBooNE results indicate that part of the NC π^0 production comes from the coherent reaction $\nu + {}^{12}\text{C} \rightarrow \nu + \pi^0 + {}^{12}\text{C}$ [3]. In future, the SciBooNE detector [4] should be able to identify π^0 's emitted in the forward direction, where most of the coherent events are concentrated, while MINERvA [5] will collect data with high statistics, allowing for a clear separation between coherent and incoherent processes and the comparison between neutrino and antineutrino cross sections.

Since the pioneering work of Ref. [2] some other studies focused on the energy region ~ 1 GeV, where the modification of the $\Delta(1232)$ spectral function inside the nuclear medium is relevant [6, 7, 8]. Pion distortion is taken into account in Refs. [2, 9] by factorizing the pion-nucleus elastic cross section (c.s.). In a more general fashion, it can be incorporated in the amplitude by means of the distorted wave Born approximation, using a pion wave function obtained in the eikonal limit [8] or by solving the Klein-Gordon equation with a realistic optical potential [7].

We have performed a theoretical study of neutrino induced coherent pion [10, 11] production extending and improving the calculations of Refs. [7, 8]. The model is built in terms of the relevant hadronic degrees of freedom: pion, nucleon and Δ resonance. Besides the dominant direct Δ excitation, it includes the crossed Δ and nucleon-pole terms [11] (see the left panel of Fig. 1). There are other contributions allowed by chiral symmetry [12] but they cancel for isospin symmetric nuclei, so we neglect them.

The relativistic amplitude is proportional to the product of the standard leptonic

current and the nuclear current, obtained as the coherent sum over all nucleons. Detailed expressions of the different contributions to the nuclear current can be found in Ref. [11]. The single-nucleon contributions to the current are parametrized in terms of vector and axial form factors (FF). The vector FF are related to the electromagnetic ones and can be extracted from electron scattering data. The axial FF are usually constrained by means of PCAC. For the $N - \Delta$ transition, this constraint is insufficient and the Adler model: $C_4^A = -C_5^A/4$, $C_3^A = 0$ is adopted. For C_5^A we consider two different parametrizations:

$$C_{5(I)}^A = C_5^A(0) \left[1 + 1.21 q^2 / (2 \text{ GeV}^2 - q^2) \right] (1 - q^2/M_{A\Delta}^2)^{-2}, \quad (1)$$

with $C_5^A(0) = 1.2$, in agreement with the off-diagonal Goldberger-Treiman (GT) relation, and $M_{A\Delta} = 1.28 \text{ GeV}$, as extracted from BNL data, and

$$C_{5(II)}^A = C_5^A(0) (1 - q^2/3M_{A\Delta}^2)^{-1} (1 - q^2/M_{A\Delta}^2)^{-2}, \quad (2)$$

with $C_5^A(0) = 0.867$ and $M_{A\Delta} = 0.985 \text{ GeV}$ as fitted in Ref. [12] to the ANL data with an invariant mass constraint of $W < 1.4 \text{ GeV}$. Notice that most quark model calculations also obtain $C_5^A(0)$ values that are smaller than the GT one (see Ref [13] for a compilation). An exception is the chiral quark model of Ref. [14] where a fluctuating σ field is taken into account.

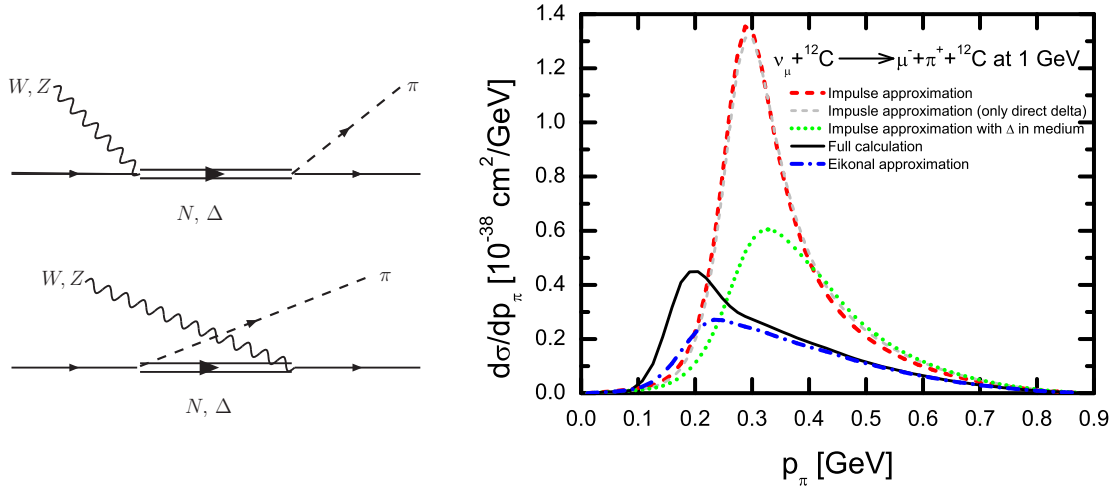


FIGURE 1. *Left panel:* Elementary reaction mechanisms for coherent pion production on isospin-symmetric nuclei. *Right panel:* Pion momentum distribution.

The pion momentum distribution for CC coherent π^+ production on ^{12}C at $E_\nu = 1 \text{ GeV}$ is presented in Fig. 1. The comparison of the two dashed lines shows that the direct Δ excitation term accounts for most of the c.s. In fact, the crossed Δ amplitude is very small, and there is a cancellation between the direct and crossed pole-nucleon ones.

The strong modification of the Δ properties inside the nuclear medium are taken into account by adding a density dependent selfenergy. This reduces the c.s. by around 35%. A realistic quantum treatment of pion distortion can be achieved by solving the Klein-Gordon equation with a microscopic optical potential \hat{V}_{opt} [15, 16] based on the Δ -hole model. Pion distortion further decreases the c.s. and moves the peak to lower energies.

TABLE 1. Cross sections for weak coherent pion production in units of 10^{-40}cm^2 , averaged over the Aachen-Padova [17], K2K [18] and MiniBooNE [19] spectra. $\sigma_{\text{I(II)}}$ correspond to the form factors I and II.

Reaction	Experiment	σ_{I}	σ_{II}	σ Experimental
NC $\nu + {}^{27}\text{Al}$	Aachen-Padova	19.9	10.1	29 ± 10 [20]
NC $\bar{\nu} + {}^{27}\text{Al}$	Aachen-Padova	19.7	9.8	25 ± 7 [20]
CC $\nu + {}^{12}\text{C}$	K2K	10.8	5.7	< 7.7 [1]*
NC $\nu + {}^{12}\text{C}$	MiniBooNE	5.0	2.6	-
NC $\bar{\nu} + {}^{12}\text{C}$	MiniBooNE	4.6	2.2	-

* Obtained using the ratio between coherent and σ^{CC} , the total CC cross section, and the value for σ^{CC} of the K2K MC simulation.

This reflects the presence of a strongly absorptive part in \hat{V}_{opt} around the Δ peak. The eikonal approximation clearly fails at $p_\pi < 400 \text{ MeV}/c$.

The c.s. averaged over the fluxes of Aachen-Padova, K2K and MiniBooNE experiments are given in Table 1. In the case of K2K the experimental threshold of $p_\mu > 450 \text{ MeV}/c$ is taken into account. The results obtained with set II are about a factor two smaller than those obtained with set I. This feature can be understood from the fact that in the forward direction ($q^2 = 0$), where most of the strength of this reaction is concentrated, the only form factor that contributes is C_5^A [21]. Therefore, one can infer that $\sigma(\text{I})/\sigma(\text{II}) \sim \left[C_{5(\text{I})}^A(0)/C_{5(\text{II})}^A(0) \right]^2 \approx 1.9$. For Aachen-Padova, σ_{I} is below the central experimental values but within the large error bars, while with set II the experiment is clearly underestimated. On the contrary, for K2K only σ_{II} is below the experimental upper bound although one should bear in mind that nuclear effects may affect the experimental separation of coherent events from incoherent ones. The situation is illustrated on the left panel of Fig. 2 where we plot the muon angular distributions averaged over the K2K flux for coherent π^+ production, together with the main contributions to the total inclusive CC cross section: quasielastic scattering (QE) and incoherent Δ excitation. The calculation of the Δ part is performed with set I. For the QE process, we have adopted the model of Ref. [22]. Nuclear effects include Fermi motion, Pauli blocking and the renormalization of the weak transition, treated as an RPA resummation of particle-hole and Δ -hole states. These nuclear correlations cause a considerable reduction of strength at low q^2 (forward angles), while they are negligible for $\cos \theta_\mu < 0.8$. Therefore, if a model that lacks these correlations is used to extrapolate the data from the region of $\cos \theta_\mu \lesssim 0.8$ to forward angles, one might overestimate the QE part, causing an underestimation of other mechanisms, like the coherent pion production.

At MiniBooNE, the measured distribution in $E_\pi(1 - \cos \theta_\pi)$ is used to extract the coherent fraction from the total NC π^0 production on ${}^{12}\text{C}$. For this reason we have performed new calculations of this observable for both coherent and incoherent π^0 production. The results are given on the right panel of Fig. 2. In order to describe incoherent pion production, the interactions of the final particles inside the nucleus have to be properly taken into account, including quasielastic scattering, charge exchange and absorption (for pions). This is achieved with the semiclassical GiBUU transport model. The details of this model and an extensive set of results for νA scattering can be found in

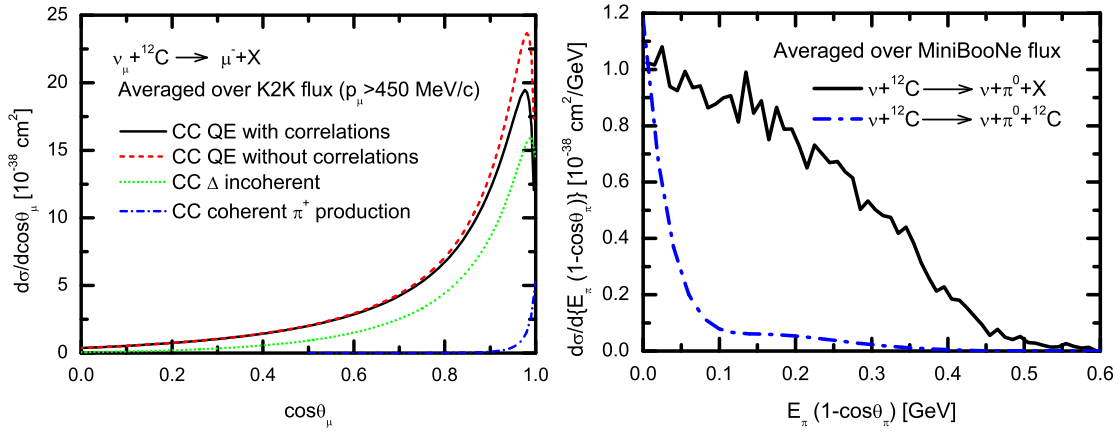


FIGURE 2. *Left panel:* Different contributions to muon angular distribution for CC processes at K2K. *Right panel:* Coherent and incoherent contributions to total NC π^0 production at MiniBooNE.

Refs. [23] and were presented by U. Mosel at this conference [24]. The coherent fraction at MiniBooNE in our model is found to be

$$\frac{\sigma(\text{coh.})}{\sigma(\text{coh.}) + \sigma(\text{incoh.})} = 0.14, \quad (3)$$

which is slightly below the preliminary value obtained by MiniBooNE [3].

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